The Discovery of Stellar Oscillations in the Planet Hosting Giant Star β Geminorum

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ABSTRACT

We present the results of a long time series of precise stellar radial velocity measurements of the planet hosting K giant star β Geminorum. A total of 20 hours of observations spanning three nights were obtained and the radial velocity variations show the presence of solar-like stellar oscillations. Our period analysis yields six significant pulsation modes that have frequencies in the range of 30 – 150 μHz. The dominant mode is at a frequency of 86.9 μHz and has an amplitude of 5.3 $\mathrm{m\,s^{-1}}$. These values are consistent with stellar oscillations for a giant star with a stellar mass of $\approx 2\ M_{\odot}$. This stellar mass implies a companion minimum mass of 2.6 $M_{Jupiter}$. β Gem is the first planet hosting giant star in which multi-periodic stellar oscillations have been detected. The study of stellar oscillations in planet hosting giant stars may provide an independent, and more accurate determination of the stellar mass.

Subject headings: planetary systems — techniques: radial velocities

1. Introduction

Radial Velocity (RV) surveys have discovered a number of giant planets in orbit around giant stars (Frink et al. 2002; Sato et al. 2003, Setiawan et al. 2003, Hatzes et al. 2005). These discoveries are important because the evolved host stars often have masses in the range 1–3 $M_{\odot}$. Precise stellar radial velocity measurements of main sequence stars in this

mass range are difficult due to the high effective temperatures of the photosphere and the paucity of stellar lines. Furthermore, these lines are often broadened by high rates of stellar rotation. Consequently, most RV surveys have focused primarily on stars later than about spectral type F6. The study of planets around giant stars can thus give us valuable clues as to the process or planet formation around stars more massive than the sun, *if* one can determine an accurate stellar mass. For giant stars this can be difficult. Evolutionary tracks of main sequence stars spanning a wide range of masses all converge to the giant branch in the color magnitude diagram. One has to rely on stellar evolutionary tracks which are model dependent, and these in turn rely on accurate determinations of such stellar parameters as effective temperature, surface gravity, abundance, and absolute luminosity.

The mass determination of Arcturus offers us a good example. Using spectral analysis Mäckle et al. (1975) determined a stellar mass of $0.1 - 0.6\ M_{\odot}$. The analysis of Martin (1977) yielded a mass in the range $0.6 - 1.3\ M_{\odot}$. This is consistent with a later mass determination of $0.95\ M_{\odot}$ by Bell, Edvardsson, and Gustafson (1985). These authors noted that due to uncertainties in the surface gravity the stellar mass could be as low as $0.7\ M_{\odot}$. An accurate stellar mass is not only important for comparing results to planet formation theories, but it is also required to calculate the companion mass. Planets around intermediate mass stars have masses in the range 3–10 $M_{Jupiter}$ and many lie on the deuterium burning border which separates brown dwarfs from planets (approximately 13 $M_{Jupiter}$). More accurate determinations of the stellar mass may establish if a companion has a mass that is still consistent with a bona fide planet or is certainly a brown dwarf, even if the orbital inclination were to be nearly 90° (i.e $\sin i = 90°$).

One of the best ways of determining stellar mass, outside of dynamical methods, is via asteroseismology. This is also the most accurate method for determining the masses of isolated stars. The stellar oscillations can be used to derive such fundamental parameters as the stellar mass, radius, age, and, depending on the number of modes detected, the internal structure. Asteroseismology has been used with spectacular success on white dwarf stars using multi-site photometric campaigns (e.g. Castanheira et al. 2004). More recently, thanks to an increase in the precision of stellar RV measurements, asteroseismology has been applied with some success to solar-like stars (e.g. Bedding et al. 2006; Bazot et al. 2005).

It is well established that many cool giants exhibit short period RV or photometric variations with periods ranging from hours (e.g. Hatzes & Cochran 1994b; Frandsen et al. 2002; de Ridder et al. 2006) to days (e.g. Hatzes & Cochran 1994a, Retter et al. 2003). These periods are consistent with p-mode oscillations in giant stars. Although many of these modes have not been identified with certainty, the observed periods seem to be consistent with radial fundamental or overtone modes (Hatzes & Cochran 1994a), although nonradial

modes can still not be excluded. The fact that extrasolar planets have been discovered around a class of stars known to exhibit stellar oscillations opens up the exciting possibility of using these stellar oscillations as an independent means of deriving important properties of the planet host star.

Long period variations with a period of 545 days were discovered in β Gem by Hatzes & Cochran (1993). One proposed explanation was that these were due to a planet with a minimum mass of 2.9 $M_{Jupiter}$, assuming a stellar mass of 2.8 $M_{\odot}$. Over a decade later Hatzes et al. (2006) and Reffert et al. (2006) confirmed that these variations were in fact due to a planet in orbit with a revised period of 590 days. Hatzes et al. (2006) used a more recent stellar mass determination of 1.7 $M_{\odot}$ to derive a companion mass of 2.3 $M_{Jupiter}$. However, given the difficulties of deriving stellar masses from evolutionary tracks of giants, β Gem could easily have a much lower or higher mass. If one is interested in understanding the stellar mass dependence of planet formation it is important to know if indeed β Gem has a mass in the intermediate (≈ 2 $M_{\odot}$) range.

Here we present time series RV measurements for β Gem taken on three nights. The star shows RV variability consistent with stellar oscillations. We then use these oscillation frequencies to estimate the stellar mass.

2. Observations

A long time series of spectral observations were made of β Gem using the coude echelle spectrograph of the 2m Alfred Jensch Telescope of the Thüringer Landessternwarte (Thuringia State Observatory). Precise stellar radial velocity measurements were achieved by using an iodine absorption cell placed in the optical light path to provide the wavelength reference. A detailed description of the instrumental setup and data reduction and analysis process can be found in Hatzes et al. (2005).

Exposure times were 90 secs and with a CCD readout time of 70 secs. The signal-to-noise ratio (S/N) of the observations depended on atmospheric transparency and seeing conditions. The S/N for our observations ranged from about 100 to 300 per pixel. A total of over 20 hours of observations were made β Gem spanning 3 different nights. Table 1 gives the journal of observations which includes the Julian day at the start of the time series, the length of the time series, and the number of spectra that were obtained. The last column is the nightly rms scatter of the RV measurements about a mult-sine fit to the data (see below).

Figure 1 shows the time series of the RV measurements on the 3 nights. It is evident

from the figure that β Gem shows low amplitude, periodic variability on short time scales. It is also clear that a single period cannot reproduce the observed variations.

3. Period Analysis

A period analysis was performed on the full data set using the program *Period04* (Lenz & Breger 2004). This program offers convenient means of searching for multiple periods in data via a pre-whitening procedure. A sine wave fit is made to the data using the dominant period found by Fourier analysis. This is subtracted and additional periods are found in the residuals by further Fourier analysis. Finally, *Period04* can be used to improve the solution by performing a simultaneous least squares fit using a sum of sine functions with the initial guess periods found in the pre-whitening procedure.

The Fourier analysis revealed a long period component corresponding to a period of 3 days. Our data string is too short to establish if this is real or possibly an alias of a shorter period. Since we are searching for periods comparable to, or shorter than our nightly coverage this long-period component was subtracted at the start of the period analysis.

Figure 2 shows the power spectra derived using the discrete Fourier transform at each step of the pre-whitening procedure. The top panel is for the "raw" time series, and each subsequent lower panel is the power spectrum after removal of the dominant frequency.

The statistical significance of the periods were assessed using a "bootstrap randomization technique". The RV values was randomly shuffled keeping the times fixed and a Scargle periodogram calculated (Scargle 1982). A Scargle periodogram was used since the power is a measure of the statistical significance of a signal. After a large number of shuffles (200,000) the fraction of random periodograms having Scargle power greater than the data periodogram gave an estimate of the false alarm probability (FAP) that a signal is due purely to noise. Our bootstrap analysis indicates that a Scargle power, $P = 15$ corresponds to a FAP $= 10^{-5}$. The pre-whitening procedure continued until the Fourier analysis found a period which we deemed not to be significant. For this analysis we considered any signal having a FAP $> 10^{-4}$ as not significant. The dominant peak in each panel of Figure 2 had Scargle power greater than 15, with the exception of the last (f_7) mode.

Table 2 lists all the periods, frequencies, and corresponding amplitudes for all the statistically significant periods found by our analysis. The modes are listed in the order they were found by the pre-whitening procedure. The first six frequencies are highly significant having FAP $< 5 \times 10^{-6}$. In other words after 2×10^5 shuffles of the bootstrap there was no instance when the power in the random periodograms had higher power than the data periodograms.

The least significant frequency is the one at ν = 193 μHz. The false alarm probability of this signal is 1.6 $\times$ 10^{-3} which is higher than our adopted threshold for significance. The amplitude of this mode is significantly less than the mean measurement error (1.5 – 2 $\mathrm{m\,s^{-1}}$). We thus regard this mode as uncertain and in need of confirmation with data spanning a longer time. The line in Fig. 1 shows the multi-component sine fit to the full data set. The rms scatter about the fit for the individual nights are 1.2, 1.5, and 1.7 $\mathrm{m\,s^{-1}}$, respectively.

4. Stellar Mass Determination

To estimate the stellar mass we used the scaling relations of Kjeldsen & Bedding (1995) which they showed to be valid for stars covering a wide range of masses and luminosity classes. In particular we will use their expression for the frequency of the maximum power:

$$\nu_{max} = \frac{M/M_\odot}{(R/R_\odot)^2\sqrt{T_{eff}/5777K}}\ 3.05\ \mathrm{mHz}$$

We chose to use this expression rather than the one for the frequency splitting because of the short time span of our observations. We are not confident that we have detected all possible modes in β Gem which are necessary for determining a frequency spacing for high order p-modes. We take the 87.9 μHz frequency as the dominant mode in the data. This has the highest amplitude and is the most obvious peak in the periodogram of the un-whitened data.

The stellar radius of β Gem has been measured with long baseline interferometry. Nordgren, Sudol, & Mozurkewich (2001) determined an angular diameter of 7.96 $\pm$ 0.09 mas which corresponds to a radius of 8.8 $\pm$ 0.1 $R_\odot$ using the Hipparcos distance of 96.74 $\pm$ 0.94 mas. McWilliam (1990) derived an effective temperature of 4850 K. Using a value of ν_{max} = 0.0868 mHz results in an stellar mass, M = 2.04 $\pm$ 0.04 $M_\odot$. The orbital solution for the companion has a mass function, $f(m)$ = (4.21 $\pm$ 0.48) $\times 10^{-9}$ $M_\odot$ (Hatzes et al. 2006). Using our nominal stellar mass results in a minimum mass for the companion, m sin i = 2.56 $\pm$ 0.5 $M_{Jupiter}$.

A caveat is in order regarding the uncertainty of our mass determination. The error is based on the uncertainties in the stellar parameters. However, the Kjeldsen & Bedding scaling relations are based on assumptions which may not be valid for a giant star like β Gem. Furthermore, due to the short time span of our measurements the frequency of maximum power may actually be in an adjacent mode. If the frequency of maximum power is actually in the modes at ν = 86.9 μHz or ν = 104.4 μHz then the stellar mass can be as low as 1.85

$M_\odot$ or as high as 2.42 $M_\odot$. We thus adopt a value of ± 0.3 $M_\odot$ as the error in our mass determination.

5. Discussion

We have detected, for the first time, stellar oscillations in a K giant star known to host an extrasolar giant planet. Our analysis reveals six significant periods, with the dominant mode at a frequency of 86.8 μHz. Using the scaling relations of Kjeldsen & Bedding (1995) as well as the interferometric stellar radius determination results in a stellar mass of 2.04 $M_\odot$. This is in reasonable agreement with the stellar mass of 1.7 $M_\odot$ used by Hatzes et al. (2006) in deriving a companion mass of 2.3 $M_{Jupiter}$. This provides independent confirmation that β Gem is indeed an intermediate mass star.

The scaling relations of Kjeldson & Bedding (1995) can also be used to predict the velocity amplitude:

$$v_{osc} = \frac{L/L_\odot}{M/M_\odot}(23.4 \pm 1.4)\ \mathrm{cm\,s^{-1}}$$

The absolute V-mag of β Gem is 1.08 mag. The effective temperature corresponds to a bolometric correction for a giant star of $BC = -0.42$ (Cox 2000) which gives a luminosity, $L = 42.8\ L_\odot$. The predicted pulsational velocity amplitude is thus $v_{osc} = 5.0 \pm 0.3$ $\mathrm{m\,s^{-1}}$, in excellent agreement with the 5.3 $\pm$ 0.38 $\mathrm{m\,s^{-1}}$ of the dominant mode.

The predicted order of the mode, n, can be estimated using Equation 10 of Kjeldson & Bedding (1995). For the stellar parameters of β Gem this corresponds to $n \approx 10$. The detected modes are most likely high order radial or non-radial modes.

The mean frequency spacing of the modes in Table 2 is approximately ≈ 20 μHz. This is considerably higher than the 7.3 μHz large spacing expected given the mass and radius of β Gem. We believe that we have not detected all possible modes due to the short time span of our measurements. Deeming (1975) showed that for modes of unequal amplitudes the modes must be separated by a frequency of 2.5/T, where T is the time span of the measurements. Our measurements have $T \approx 3$ days which corresponds to $\delta\nu = 8.8$ μHz. Furthermore, we do not know what the mode lifetimes are. Continuous measurements spanning a week or more may be required to derive the full oscillation spectrum of β Gem.

Our investigation of β Gem shows the potential of using stellar oscillations to determine the stellar mass of giant stars. We suspect that stellar oscillations in K giant stars are

ubiquitous. If that is the case, then an investigation of the stellar oscillations in planet hosting giant star can be used to determine a more accurate stellar mass. We are aware that our mass estimate is only an approximation. More modes need to be detected in β Gem and a proper theoretical modeling is required to derive a more accurate stellar mass. We are currently analyzing additional RV measurements for this star to search for additional modes.

As is the case with ground-based asteroseismic studies it is very difficult to get the requisite telescope time needed detect all possible modes. Observations using multi-site campaigns are needed due to the one day alias at single sites. This could be difficult because not all astronomical facilities are equipped for making precise stellar RV measurements. Furthermore, even with multiple observing sites, poor weather conditions at one or more sites can still produce data gaps. In this respect the CoRoT space telescope (Baglin et al. 2001) will provide a major breakthrough in the study of K giant oscillations. CoRoT is a 27cm telescope with a dual mission – asteroseismology on bright stars and a search for transiting exoplanets in a field of up to 12,000 stars in the visual magnitude range $V =$ 11–16. CoRoT can achieve a photometric precision of $\approx 2 \times 10^{-4}$ in one hour for a star in the exofield with $V = 15.4$. CoRoT was launched on 27 December 2007 and as of this writing the light curves from the first observed field had not yet been released.

The Kjeldsen & Bedding (1995) scaling relations yield a predicted photometric amplitude of 100 ppm (10^{-4}) for a giant star exhibiting stellar oscillations like β Gem, a precision that can be reached for most stars in the CoRoT exofield, and many of these will be giant stars. The 150-day, uninterrupted observations of a given long run CoRoT field should yield the full oscillation spectrum for stars throughout the giant branch. Given that sub-stellar companions may be common around giant stars a search for companion around pulsating K giants found by CoRoT should prove fruitful for planet formation studies.

Acknowledgments

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Table 1. Journal of Observations

Start (Julian Day)	Time Coverage (hours)	N_{Obs}	σ ($\mathrm{m\,s^{-1}}$)
2450168.308	6.88	115	1.2
2450170.266	5.04	74	1.5
2450171.259	8.64	152	1.7

Table 2. Oscillation modes for β Gem

Mode	Period (hours)	Frequency μHz	Amplitude $\mathrm{m\,s^{-1}}$
f_1	3.20	86.91 ± 0.37	5.29 ± 0.38
f_2	2.66	104.40 ± 0.49	4.09 ± 0.28
f_3	9.34	29.75 ± 0.54	3.61 ± 0.22
f_4	6.23	48.41 ± 1.06	1.85 ± 0.18
f_5	3.85	79.47 ± 0.76	2.58 ± 0.16
f_6	2.02	149.25 ± 0.63	1.25 ± 0.15
f_7	1.56	193.63 ± 3.07	0.64 ± 0.13

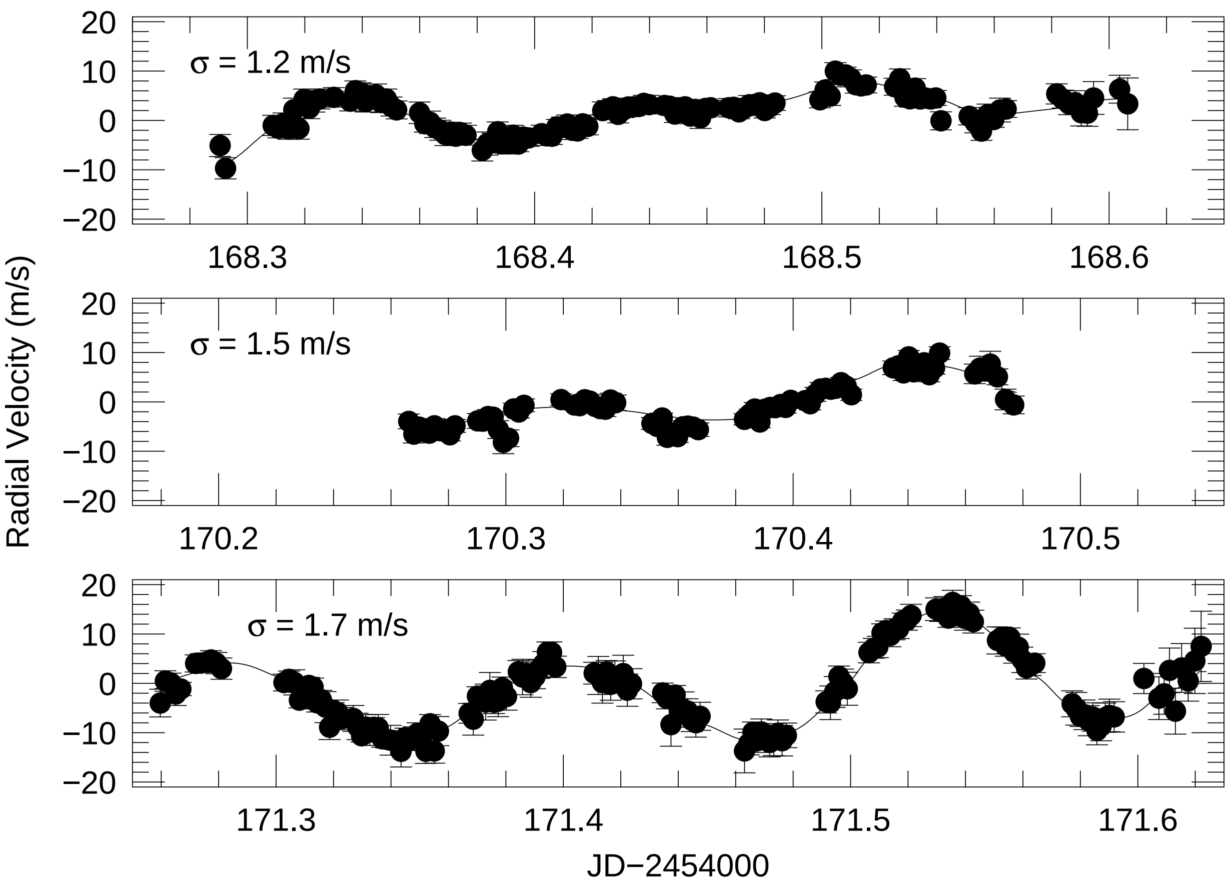

Fig. 1.— Time series of the RV measurements for β Gem for three nights. The line represents a multi-component sine fit using the six frequencies of Table 1. The standard deviations of the RV values about this fit are 1.2, 1.5, and 1.7 $\mathrm{m\,s^{-1}}$ on the three nights, respectively.

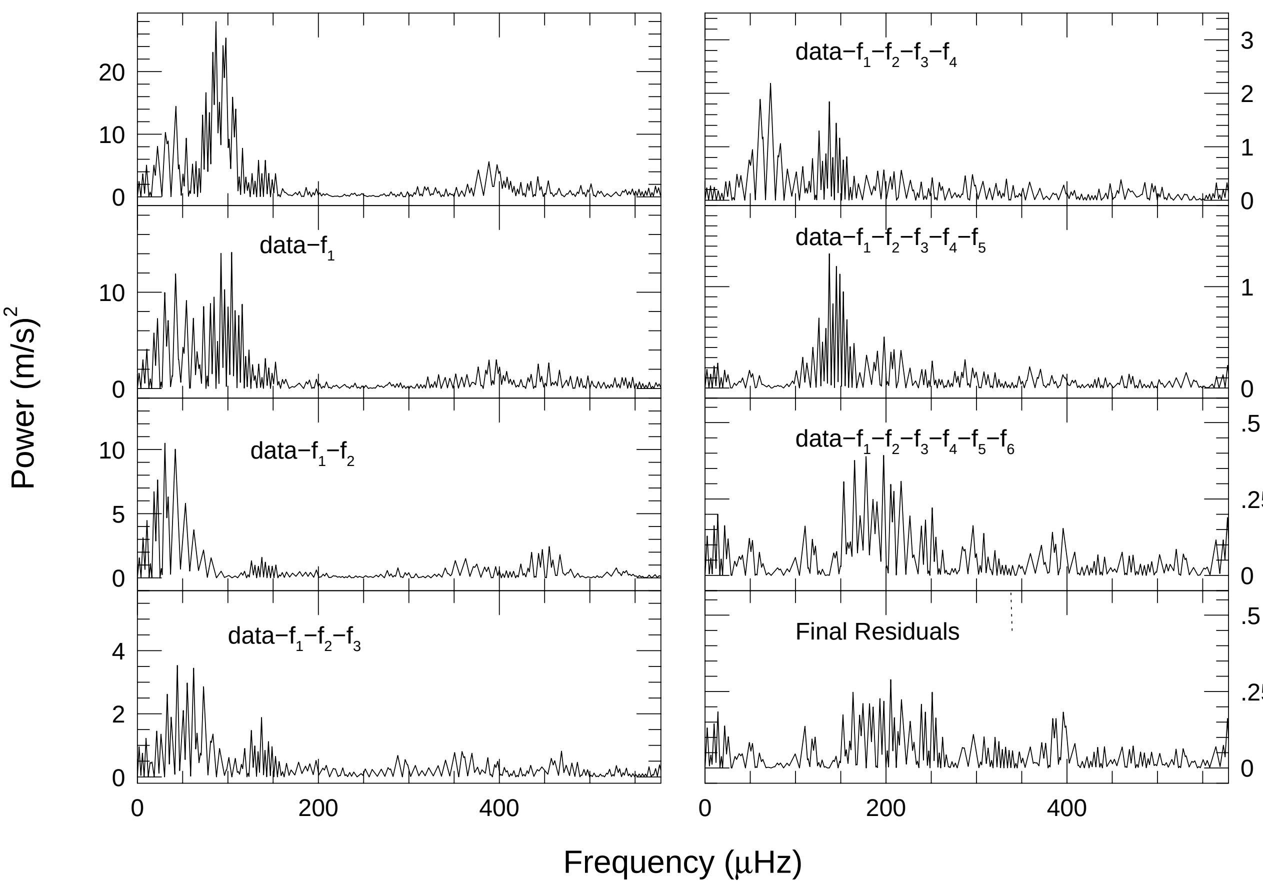

Fig. 2.— Power spectra of the RV data at each step of the pre-whitening procedure. The top left panel is for the raw RV data. Each successive lower panel shows the power spectrum after subtracting the contribution of the dominant mode from the previous (upper adjacent) panel. The lower right panel is for the final RV residuals after removal of the possible seventh mode (f_7). Note the change in y-axis scale for each panel.